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ROLLING MILL INSTRUMENTATION.

By C. W. STARLING, B.Eng., A M.I.Mech.E.

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ROLLING MILL INSTRUMENTATION.

A Survey of the Industrial Type Instruments Developed and Built in the B.I.S.R.A. Laboratories over the last Ten Years.

By C. W. STARLING, B.Eng., A.M.I.Mech.E.

This manuscript was prepared in the summer of 1954 and deals with developments up to that date.

I. INTRODUCTION.

In order to carry out research into the deformation of metals by rolling, an experimental mill was equipped with instruments for measuring roll force, strip tension and roll torque. The instruments were designed and built in the B.I.S.R.A. laboratories and after many months of satisfactory performance a range of prototype instruments suitable for the arduous duties of a production mill were developed from them.

Prototype loadmeters have been built in a range of sizes from 25 to 1200 tons maximum load and tested thoroughly under production conditions. Apart from the obvious duty of measuring the load on the rolls, the loadmeter is an invaluable piece of equipment as it supplies a signal which forms an essential part of the B.I.S.R.A. gaugemeter and automatic gauge control (A.G.C.) systems.

Several types of strip tension meter have been tested, both in the laboratory and under production conditions, and the type to be used for a particular application must be considered in relation to the layout of the mill and coilers and the accuracy required.

The torquemeter is of interest to mill designers rather than a direct help in mill operation, but it is described in detail as a torquemeter forms the basis of one type of tensiometer.

In a pamphlet of this nature it is impossible to describe fully the design of each instrument, but the design principles are discussed in sufficient detail to allow a competent designer to decide whether any of the instruments could be fitted to a specific mill, and to design the mechanical components. The basic electrical circuits are considered, but the more advanced A.C. systems are outside the scope of this pamphlet.

II. THE ELECTRICAL RESISTANCE STRAIN GAUGE.

As all the instruments described depend on the strain gauge for their operation, this section describes the elementary principle and the practical application.

Principle of Strain Gauge.

Simple experiments have shown that if a wire is strained, its electrical resistance varies and if the resistance is measured very accurately for various values of positive and negative strain a unique curve can be obtained of the general form shown in Fig. 1, where δR is the change in resistance from the initial resistance R and δL is the change in length from the original length L. In subsequent tests with this wire, it is then sufficient to measure the change of resistance, and the strain can be obtained from the curve. In practice, it is not necessary to obtain this curve each time. The strain gauge manufacturer selects a wire of suitable material which will give a linear region at each side of zero, then obtains the dimensionless constant $\frac{\delta R/R}{\delta L/L}$, known as the "gauge factor" or the "gauge sensitivity" and guarantees it to within a given tolerance, usually $\pm$ 1%. It is then only necessary to measure the change in resistance and apply this factor to obtain the strain.

In order to measure the strain in an object, a very fine wire is bonded to it, so that any strain in the object is transmitted to it, and the change in resistance of the wire measured.

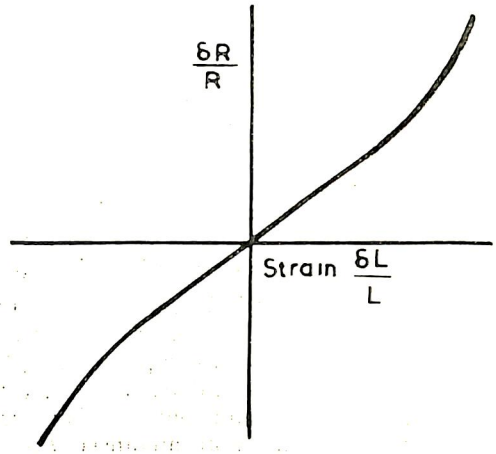


Fig. 1—Variation of Electrical Resistance with Strain.

Practical Application of Strain Gauge.

In practice, the single strand of wire is not satisfactory for most applications, chiefly because of the length required to give a measurable change in resistance for small strains, and the usual procedure is to make up a compact gauge from a long length of wire by forming it into a grid. The gauge most widely used in this country consists of approximately 40 in. of 0·001 in. dia. wire wound on a paper former which has been impregnated with resin. Small strips of cupronickel or similar material are welded to each end of the wire so that when the gauge is applied it is relatively easy to solder on the leads. A bonding agent is then applied to both sides and the gauge sandwiched between two pieces of tissue paper to form a compact and robust unit, 1″ long. Other sizes from $\frac{1}{8}$″ to $1\frac{1}{2}$″ long can be obtained, and manufacturers will make up any size to special order.

The resistance of this type of gauge is usually in the order of 2500 ohms, and the insulation between the gauge and specimen must be very good (not less than 120 megohms).

With the very high degree of voltage amplification possible in an A.C. measuring system, it has been found that low resistance gauges can be used. These are known as "foil" gauges and consist of foil usually ·0005″ thick, etched to a grid shape and mounted on a thin sheet of synthetic resin. As they are perfectly flat, it is easier to obtain a good bonded joint between the gauge and specimen than it is with round section wire.

The recommended current for a wire gauge is about 5mA with an absolute maximum of 10mA if long term accuracy is required. With foil gauges, however, much higher currents are possible, the limit depending on the rate of heat dissipation for a given application. When the foil gauges are attached to a large mass of metal a current of around 100mA is satisfactory. The foil gauges appear to be more susceptible to temperature drift than the wire ones.

The range of strain over which the sensitivity will be within the guaranteed tolerance can be obtained from the manufacturer of any particular gauge, but for the types in common use it is safe to take 0·2% strain as a maximum.

Gauge Fixing Technique.

There are two fixing techniques in current use in the B.I.S.R.A. laboratories. The simplest system, in which durofix is used as the bonding agent, is applied to bulky articles or components which are difficult to dismantle, but is only satisfactory when the temperature will not exceed 20°C. For higher temperatures, to a limit of about 70°C., a thermo-setting resin is used.

In either case, the surface of the metal is first prepared by removing any scale, rust or surface finish such as plating or anodising, and roughened slightly with very fine glass paper. It is then swabbed with cotton wool dipped in acetone or some similar solvent to remove all traces of grease. This must be done in a warm dry atmosphere to prevent any traces of moisture forming, and the gauges should be stored in a dessicator in a warm cupboard.

If durofix is to be used, a thin layer is brushed on the surface of the specimen and left to dry completely. The gauges can be obtained from the manufacturer with a durofix coating on the paper backing and after dipping quickly in acetone, they are applied directly to the prepared surface of the specimen. The acetone softens both layers of durofix, and the gauge is pressed firmly in position from the centre outwards, taking care to remove all air bubbles. On a flat surface it is sufficient to leave the gauge to set after pressing very firmly into position, but on a curved surface it is advisable to bind tape round and leave for 48 hours at room temperature.

If *Araldite*, a proprietary brand of synthetic resin is to be used, the technique is a little more difficult. A thin layer of *Araldite* is brushed onto the prepared surface of the specimen, and a similar layer on the back of the gauge. They are then allowed to dry at room temperature until just tacky, and the gauge pressed firmly into position, as before, then clamped. As most of the gauges are attached to shafts and similar curved surfaces they are clamped in position by wrapping with thin cork sheet, followed by linen strip which is stretched tightly and the ends sewn up. The linen is well brushed with an amyl acetate compound which shrinks it and holds the gauges firmly in contact with the specimen. The whole assembly is then put in a cool oven, brought slowly up to 160°/170°C. and maintained at this temperature for four hours, after which it is allowed to cool gradually in the oven.

As mentioned earlier, great care must be taken to eliminate any traces of moisture. This is necessary to obtain absolute adhesion, but even after the gauge is in position it must be kept completely dry. Any moisture which forms may cause breakdown of the insulation between the gauge and specimen, or can cause electrochemical corrosion of the gauge wire, thereby increasing its resistance considerably. There are several waterproofing techniques in current use, many of which make use of *Di-jell*, a proprietary water repellant substance of the consistency of very thick grease, which is packed all round the gauges.

At the time of writing, a specimen of a new strain gauge cement developed by Aero Research, Ltd., is being tested. This simplifies the application of strain gauges considerably. The cement is obtained as a black viscous fluid in a sealed tin, together with a

bottle of hardener. Just before use, a few drops of hardener are mixed with the cement which is then brushed on to the surface of the specimen and the gauge pressed firmly into position. The curing time varies from 24 hours at room temperature to 20 minutes at 100°C. After soldering on the connecting wires, cement can be brushed over the gauges to form a waterproof, protective coating.

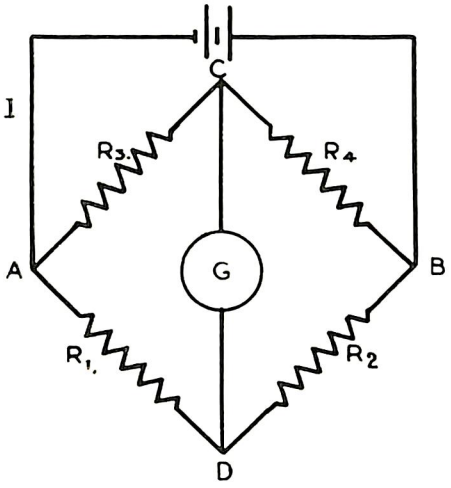


Fig. 2—Simple Wheatstone Bridge.

Measurement of Resistance Change.

Most methods of measuring change in resistance accurately are based on the simple Wheatstone bridge shown in Fig. 2.

In this circuit, $\frac{R_3}{R_1} = \frac{R_4}{R_2}$ when the bridge is in balance with the galvanometer reading zero. The simplest strain measurement is obtained by having three known resistances (usually dummy gauges) in three arms of the bridge, with the gauge mounted on the specimen under test in the fourth arm. The known resistances are fixed at values which give a balanced bridge when the test gauge is unstrained. Any strain of the test piece will then cause a deflection of the galvanometer, either positive or negative, depending on whether the strain is tensile or compressive. The galvanometer can be calibrated directly by subjecting the specimen to known strains.

Another method is to have a slide wire mounted between R_1 and R_2 as shown in Fig. 3. If the bridge is unbalanced by straining R_4, it is rebalanced by means of the slide wire.

Then $$\frac{R_3}{R_1+r_1} = \frac{R_4}{R_2+r_2}$$

Slight changes in contact resistance will affect the sensitivity of the galvanometer, but will not affect the point of balance of the bridge. As before, it is possible to calculate change of resistance and hence strain in the specimen from the degree of unbalance of the bridge, but a direct calibration from known strains is required for accurate work.

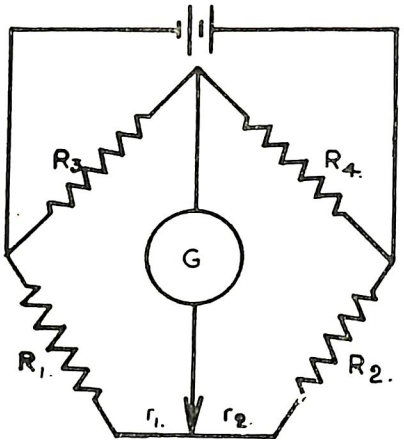


Fig. 3—Balanced Wheatstone Bridge.

III. THE LOADMETER.

Design Principles.

The load measuring element is a solid steel cylinder with a network of strain gauges bonded to its surface, which is mounted between the top chock and the screw. It is, therefore, subjected to the full separating force on the rolls and will be compressed elastically. The compressive strain is measured by means of the strain gauges and converted to a stress and hence to the roll load.

The size of the cylinder is governed by the maximum permissible strain. If the resistance changes are to be measured by a simple D.C. system without amplification the strain should be relatively high in order to obtain as large a deflection as possible on a micro-

ammeter. An absolute maximum of 0·2% strain is suggested when E.N. 17 steel is used. If the strain gauge output is amplified by an A.C. system it is possible to obtain accurate measurements with strains of less than 0·1%.

The length/diameter (L/D) ratio of the cylinder is very important. In practice it is not always possible to ensure that the load is applied to the cylinder axially, or that it is evenly distributed across the loading face. This may lead to an uneven distribution of surface strain round the circumference of the cylinder, and to misleading readings from the strain gauges. A system of forces of this type is covered by St. Venants principle, which states, in brief, that the distribution of the load has a negligible effect on the stresses at distances from the point of application which are large compared with the linear dimensions of the surface to which the load is applied. Applying this to the load cylinder, if the L/D ratio is large so that the strain gauges are at a considerable distance from the loading face, eccentric loading should have little effect on the results. Because of space limitations in existing mills, however, it is usually not possible to use a large L/D ratio ; and good results have been obtained with the length equal to the diameter, provided that care is taken with the mechanical design to eliminate eccentric loading as far as possible. L/D ratios less than unity are not recommended except in the few cases where approximate load measurements are required to within say ± 5%.

Mechanical Design Details.

A typical loadmeter assembly is shown in Fig. 4. (A) is the load measuring element. The choice of material for this is important, as it must remain completely elastic at the maximum design stress, and should have a minimum of elastic hysteresis, *i.e.*, given stresses should always produce the same strains on loading or unloading. A suitable steel for the high stresses required when using a simple D.C. Wheatstone bridge network has been found to be E.N. 17, which is hot forged then heat treated to give a yield stress not less than 34 tons/sq. ins.

The flange must be relieved on the underside so that it does not carry any load.

A heavy cover (B) provides mechanical protection for the strain gauges and transmits the screw torque to the mill frame. By fitting suitable seals on the flange, some measure of waterproofing is obtained. It has been found necessary to fit a thin disc of friction material between the top of the cylinder and the cover to prevent any slip between the two during loading, otherwise the calibration consists of a series of very shallow steps. The clearance between the cover and the flange must be sufficient to allow compression of the cylinder and the friction pad, as it is

imperative that none of the applied load should be taken by the cover. For the same reason, the resistance to compression of any sealing rings must be small, and if the cover is held to the flange by dowels and studs, the studs should not be tightened sufficiently to put a pre-load on the cylinder. The top of the cover on which the load is applied must be ground and polished to a mirror finish in order to keep the torque transmitted through the cover as low as possible.

The load from the rotating screw is transferred to the top of the cover through a bearing cap (C). This has a phosphor bronze insert (D) which is a good running fit on the cover, and a thrust pad (E) of a resin bonded laminated fabric such as *Tufnol*. The surface of the cap in contact with the thrust pad is also ground and polished to a mirror finish. Provision must be made for injecting a good alkaline oil into the thrust bearing. The screw should be a good fit in the top of the bearing cap.

When screwing down under load, the bearing cap will exert a twisting moment on the main assembly, approximately equal to $\frac{2}{3}\mu r P$,

where μ = coefficient of friction of thrust bearing (approx. ·08).

r = radius of thrust bearing.

P = total screwdown load on the cap.

The assembly must, therefore, be restrained by locating the base on the chock, or by welding a lug on the side of the cover and attaching it to the mill frame by a torque link and universal joint, capable of withstanding this load.

Provision must be made for getting the wires from the strain gauge bridge through the cover. The present system consists of a thick walled tube welded to the cover, with a union nut at its outer end, to which an armoured hose is attached.

The complete assembly is shown in the photograph (Fig. 5).

Arrangement of Strain Gauges.

In the simple Wheatstone bridge circuit discussed earlier, it was suggested that the live gauge in one arm of the bridge balanced against dummy gauges in the other arms. This will compensate for any change in resistance due to the heating effect of the current passing through the gauges but in practice the metal to which the measuring gauge is bonded may undergo considerable temperature changes. It is, therefore, essential that all the gauges are actually mounted on the measuring element in order to provide a high degree of temperature compensation. Obviously, the gauges cannot all be mounted in the same direction, or the strain in each would be

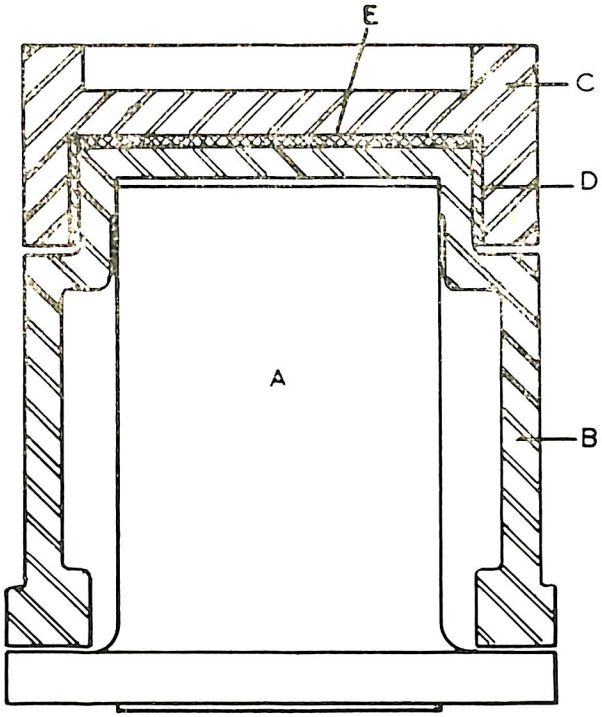


Fig. 4—A Typical Loadmeter.

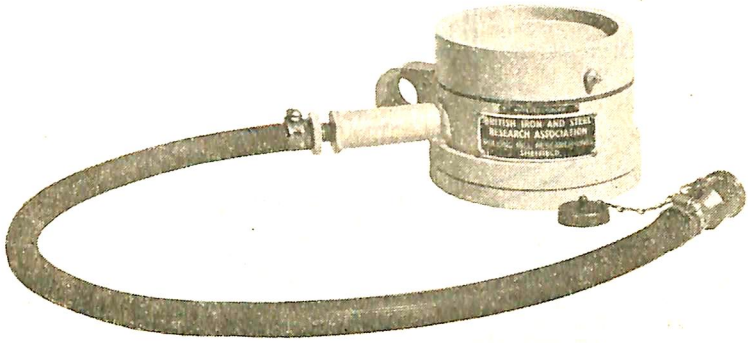


Fig. 5—300 Ton Loadmeter.

identical and the bridge always in balance. They are, therefore, mounted alternately horizontally and vertically, the horizontal ones being equivalent to the "dummy" gauges in a simple circuit. In actual practice, however, the vertical gauges are under compressive strain, and their resistance decreases under load, whereas the resistance of the horizontal ones will increase slightly, due to the hoop tensile strain. All the gauges are, therefore, contributing towards the "out of balance" effect.

As it is usually not possible to use a high L/D ratio, it is probable that any non-axial loading will cause a variation in stress around the circumference at the measuring plane. It would, therefore, be advantageous to have a large number of gauges distributed equally round the cylinder, in order to obtain the mean stress. It is normally possible to fit eight gauges, four horizontal and four vertical, identical gauges at opposite ends of a diameter having their outputs added in each arm of the bridge. The final arrangement of gauges is then as shown in Fig. 6, and they are wired into a Wheatstone bridge as shown in Fig. 7.

The bridge wiring is taped to the cylinder, and the whole electrical assembly protected by rubber tape, bound round and bonded to the metal. The bridge input and output leads are brought out through this covering and pass through the tube and armoured hose attached to the cover. On assembly the whole of the cavity between cover and cylinder can be packed with *Di-jell*

This completes the actual load measuring unit.

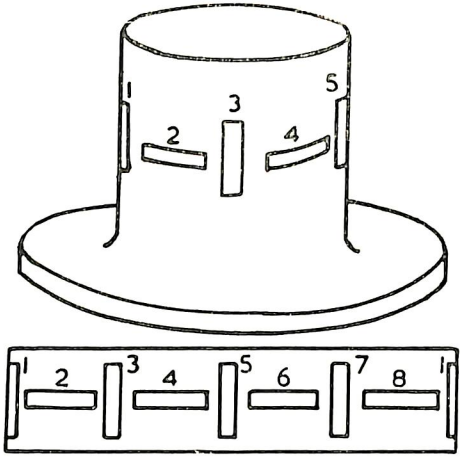


Fig. 6—Arrangement of Strain Gauges on Loadmeter.

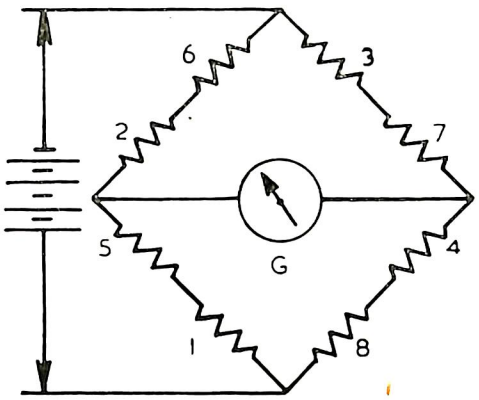


Fig. 7—Arrangement of Loadmeter Gauges in Wheatstone Bridge.

Calibration of Loadmeter.

The simplest measurement of load is obtained from the circuit shown in Fig. 7, where the input voltage is held constant at a known value and the bridge "out of balance" measured by the deflection of a high grade microammeter. The deflection to be expected from a given load can be obtained from the equation

$$\frac{P}{I_G} = \frac{2\pi r^2 E\,(R_S+R_G)}{(1+\sigma)\;\lambda\,V_S} \text{ Tons/Amp.}$$

where P = load to be measured.

I_G = out of balance current from the microammeter.

r = radius of measuring cylinder.

E = Young's modulus.

σ = Poisson's ratio.

λ = gauge sensitivity.

V_S = voltage across the bridge.

R_G = resistance of ammeter.

R_S = Net resistance between A and B, obtained by replacing the battery by a wire of negligible resistance.

The derivation of this formula is given as a matter of interest.

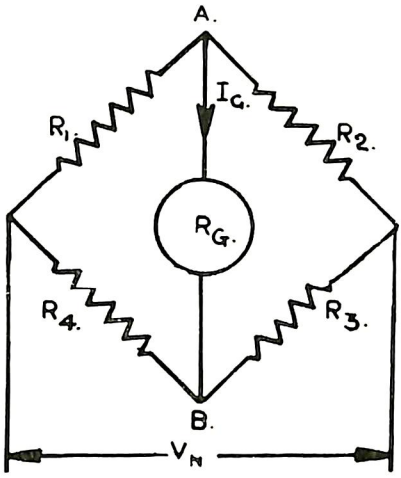


Fig. 8—Gentral Calibration Circuit.

In the general case, Fig. 8.

Potential of point A compared with battery terminal is

$$\frac{R_2}{R_1+R_2}\ V_N$$

and of point B is

$$\frac{R_3}{R_3+R_4}\ V_N$$

Then $$V_{AB} = \left(\frac{R_2}{R_1+R_2} - \frac{R_3}{R_3+R_4}\right) V_N \qquad (1)$$

and $$I_G = \frac{V_{AB}}{R_N+R_G}$$

Applying this to a loadmeter, we obtain gauges which are all matched to an initial resistance R. Assume the vertical gauges decrease in resistance by $\triangle R$ and the horizontal ones increase by $\triangle Q$, then the strain condition is represented in Fig. 9.

Substituting these values in the general equations

$$V_{AB} = \left(\frac{R+\triangle Q}{2R+\triangle Q-\triangle R} - \frac{R-\triangle R}{2R+\triangle Q-\triangle R}\right) V_N$$

$$= \left(\frac{\triangle Q+\triangle R}{2R+\triangle Q-\triangle R}\right) V_N$$

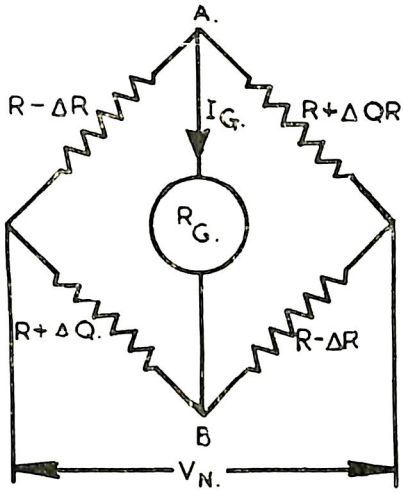


Fig. 9—Calibration Circuit After Straining.

$\triangle Q - \triangle R$ will be very small compared with 2R and may be neglected.

$$\text{Then } V_{AB} = \left(\frac{\triangle Q + \triangle R}{2R}\right) V_N$$

$$\text{and } I_G = \frac{\left(\frac{\triangle Q + \triangle R}{2R}\right) V_N}{R_N + R_G}$$

If λ is sensitivity of gauge and $\triangle R$ is change in resistance for strain ϵ from definition

$$\frac{\triangle R}{R} = \lambda \epsilon \qquad (2)$$

The equivalent horizontal strain will be $\sigma\epsilon$ where $\sigma \simeq \frac{1}{3}$.

$$\text{and } \frac{\triangle Q}{R} = \lambda \sigma \epsilon.$$

$$i.e., \ \triangle Q = \sigma \triangle R.$$

Then eliminating $\triangle Q$ from the equation for I_G

$$I_G = \frac{\triangle R}{2R} \quad \frac{(1+\sigma) V_N}{R_N + R_G}$$

$$\text{or } I_G = \frac{(1+\sigma)}{2 (R_N + R_G)} \frac{\lambda \epsilon V_N}{}$$

Strain in the cylinder is given by

$$\epsilon = \frac{P}{\pi r^2 E}$$

and if this value is substituted in the equation for I_G it gives

$$I_G = \frac{(1+\sigma)\ \lambda\ V_N\ P}{2\pi r^2 E\ (R_N+R_G)}$$

or calibration factor

$$\frac{P}{I_G} = \frac{2\pi r^2 E\ (R_N+R_G)}{(1+\sigma)\ \lambda\ V_N} \text{ tons/amp.}$$

All the factors in this equation are known, and it is possible to scale a microammeter directly in tons.

This calibration may be satisfactory for normal mill operation, but for accurate work each individual cylinder should be calibrated with its own microammeter. This is done simply by subjecting the loadmeter to various accurately known loads and marking the ammeter scale to correspond with them. A general calibration is obtained by replacing the ammeter by a vernier potentiometer and measuring very accurately the voltage input and output from the bridge.

Load Indicator Circuits.

The simplest load indicator circuit is the one described above, where there is a D.C. supply and the output is shown directly on a microammeter scaled in tons. If the intention is to have a portable system, which will be fitted to a mill to obtain a rolling schedule, then removed, a self-contained battery operated unit can be made. This is simply a box to contain suitable high capacity dry batteries, a volt meter, microammeters and the other components shown in the circuit diagram, and with two sockets to which the leads from the load cylinders are attached. The plugs and sockets should be coloured, to ensure that each load cylinder is always attached to the same circuit. For ease of handling, various additions are made to the simple circuit and these are shown in Fig. 10.

The supply is obtained from batteries, the voltage input to the bridge being held constant by fine and coarse rheostats A and B. During calibration of Bridge 1, rheostats C are adjusted so that the maximum load gives a full scale deflection of the ammeter, then locked in this position before final calibration. Similarly, Bridge 2 is controlled by rheostats D.

The outputs from each bridge are read from microammeters and there is provision for switching the outputs in parallel to obtain an approximate reading of total load on a single meter.

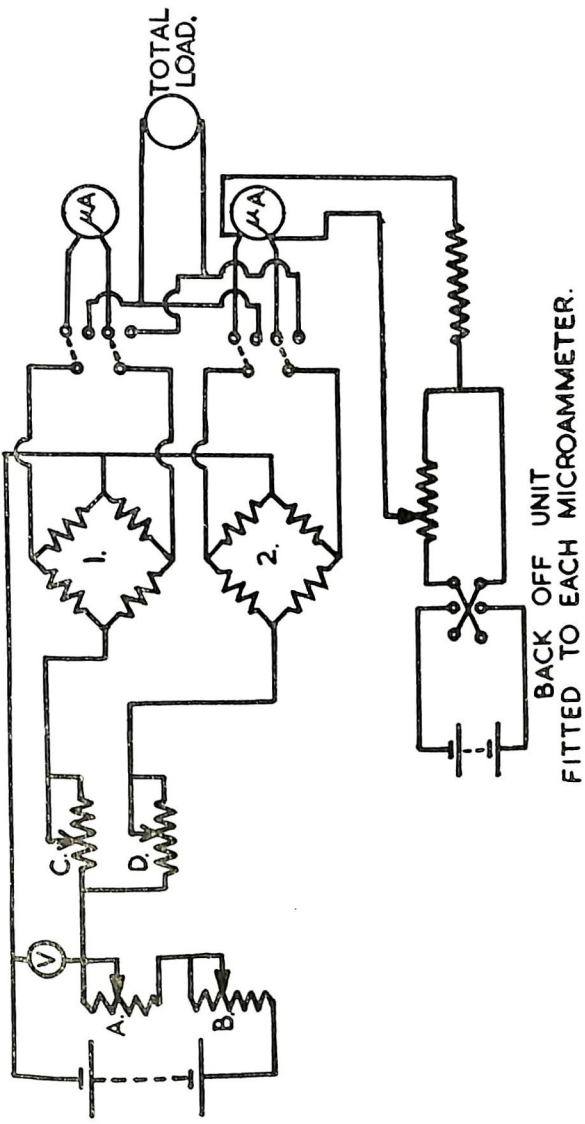


Fig. 10—Portable D.C. Loadmeter Circuit.

The back-off units, consisting of battery, reversing switch and variable resistance are incorporated as a simple means of adjusting the zero of the ammeters. A photograph of the complete set is shown in Fig. 11.

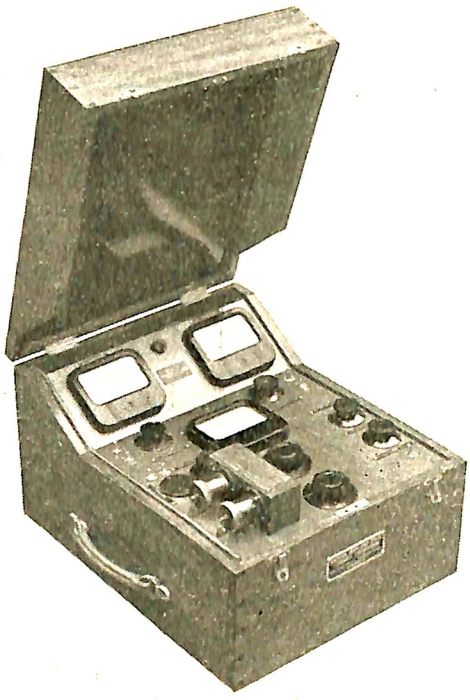


Fig. 11—Portable Loadmeter Equipment.

For a permanent installation, the batteries can be replaced by a stabilised power supply, to give a constant D.C. supply from the mains, independent of the mains fluctuations. This type of power supply can be obtained commercially.

The chief disadvantage of this system as a permanent installation is that the microammeters are delicate instruments and can only be obtained in quite small sizes. This means that they cannot be mounted on the mill stand, but have to be on the control desk.

The simplest A.C. indicating system is a direct development of the above D.C. system. The D.C. supply is replaced by a power supply and oscillator which feed the two bridges at 400 or 500 c.p.s. The output from each bridge is taken to its own

amplifier, and the loads indicated on milliammeters. During calibration of this system, each amplifier is adjusted to give a full scale deflection on its own milliammeter for the maximum load. The advantage of this system over the D.C. is that the milliammeters are more robust and can be obtained with $6\frac{1}{2}''$ diameter scales. They are still not suitable for mounting on the mill housing.

The A.C. potentiometric system is the one considered to be most satisfactory for permanent installation as the load indicating

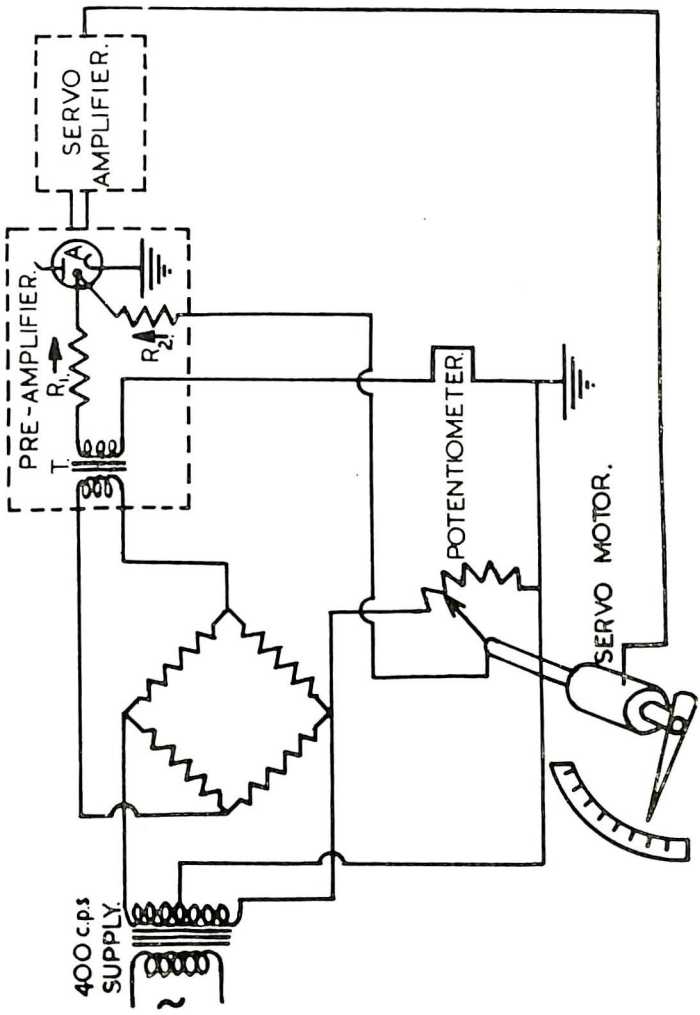


Fig. 12—Principle of A.C. Potentiometric Circuit.

pointers are driven mechanically and therefore can be made to any size required and mounted on the mill stand at any convenient point. A much simplified diagram of the system is shown in Fig. 12. The strain gauge bridge is supplied with A.C. at 400 c.p.s. and the output transformed to a higher voltage at T. This voltage is compared at point A with a voltage obtained from the input supply and adjusted by a circular potentiometer. When the bridge is in balance, the potential at A is zero, but if the bridge is unbalanced by straining the gauges a voltage is produced at A. This is amplified and operates a small servo motor which drives the potentiometer in the appropriate direction until a balance is again reached.

The angular position of the potentiometer is therefore a direct indication of the "out of balance" of the bridge and by means of a suitably calibrated scale, a pointer attached to the servo motor shaft will read the load directly in tons.

Although this is a relatively straightforward application of the Wheatstone bridge, the detail design of the electronics becomes quite complicated and a system using standard interchangeable units is discussed fully in a paper being published by S. S. Carlisle and G. Alderton.

IV. THE TORQUEMETER.

The measurement of the torque transmitted by a rotating shaft is a problem common to many branches of engineering. There are many types of torquemeter available commercially, but the spindles driving the rolls of a rolling mill are usually short and very close together and it has been found to be almost impossible to fit a conventional instrument. Roll driving spindles, particularly in a hot reversing mill are subject to very rapid and heavy fluctuations in torque and the measurement of shear strain in the shaft by strain gauges is one of the simplest methods which will give a sufficiently rapid response. The strain gauge torquemeter is not entirely new, but various models have been designed and built in the B.I.S.R.A. laboratories specifically to withstand the conditions obtaining on production rolling mills.

The strain gauges are mounted at 45° to the axis of the shaft and measure shear strain, connections between the gauge network and the indicating circuits being through slip rings, which must be very carefully designed both mechanically and electrically.

Arrangement of Strain Gauges.

In order to form a temperature compensated network, a minimum of four gauges must be attached to the shaft and as the maxi-

mum principal strain is at 45° to the axis the gauges are set at this angle. One possible arrangement is shown in Fig. 13 (*a*). When the shaft is twisted, gauges opposite to each other, say 1 and 3, will be extended and increase in resistance whereas the other pair, 2 and 4, will decrease in resistance. They could then be linked together in a simple network, Fig. 13 (*b*). This arrangement would be satisfactory for a shaft in universal joints transmitting pure torque, but as this condition is rarely realised in practice, allowance has to be made for errors caused by bending. This is done by mounting the gauges in pairs at each end of a diameter, and connecting them up as shown in Fig. 14. It is possible to obtain this type of crossed gauge made up as a unit by the manufacturer. If the diameter on which the strain gauges are attached is normal to the plane of bending, 1 and 2, say, will increase in resistance by the same amount as 3 and 4 decrease, and by wiring them into the Wheatstone bridge in the order shown the change due to bending will not affect the bridge output. Similarly at any other angular position the bending effect will produce equal and opposite changes in resistance on the pairs of gauges. After cementing the gauges in position the bridge is wired up and taped to the shaft, as described for the loadmeters, the input and output leads being attached to the slip rings. The waterproofing to be used depends on the size of the shaft. On a very large shaft it is most convenient to waterproof each pair of gauges separately. To do this, the area surrounding the gauges is degreased and given two coats of *Linatex Solufix No.* 9 cement. A rubber surround is cut from $\frac{3}{64}$ in. *Linatex* sheet, degreased, coated with *Solufix No.* 7 cement and allowed to dry for about twenty minutes. At the same time the surface of the cement already on the shaft is coated with No. 7 cement. The rubber wall is then put in position and hammered to make a good bond. This stage is shown in Fig. 15 (*a*). A second wall is cut from *Linatex* sheet, with slots for the wires to pass through. This is attached to the first wall by No. 7 cement and hammered into position. The cavity is filled with *Di-Jell* and the seal completed by bonding a further rubber sheet on top. (Fig. 15 (*b*)).

For small diameter shafts it is more convenient to form the box by bonding *Linatex* walls all the way round the shaft as shown in Fig. 16. The waterproofing is then completed as for the individual gauge assemblies. If it is probable that the shafts will be continually in contact with grease or oil the rubber should be protected by *Neoprene* tape.

With the larger diameter shafts it is usually possible to mount the slip ring unit over the strain gauges, so giving them mechanical protection.

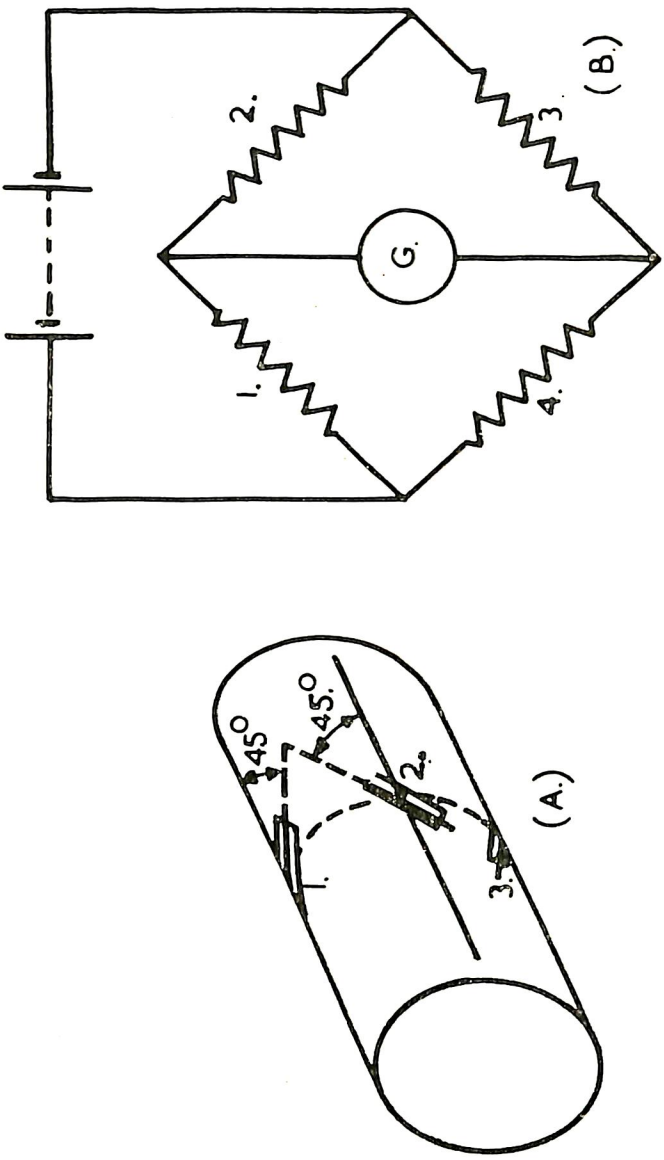


Fig. 13—Arrangement of Strain Gauges for Torquemeter. (No Bending).

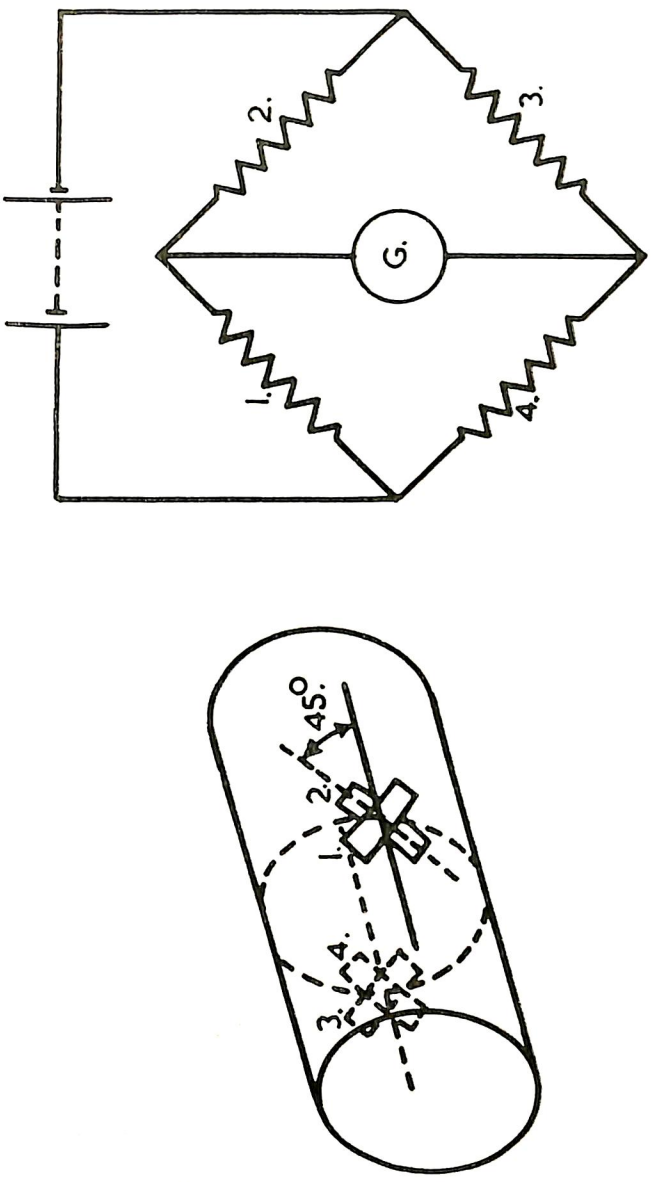


Fig. 14—Arrangement of Strain Gauges for Torquemeter. (Corrected for Bending).

Design of the Slip Ring Unit.

The slip ring unit is a straightforward design problem, which will have to be studied in relation to the shafts to which the torquemeters are to be fitted. The general design principles are given, and examples of two widely different types which have been used. The critical factor is the choice of materials for the slip rings and brushes. The requirements are that their contact potential and resistance should be small and constant over a wide range of rubbing speeds and that the "noise" induced by them in an amplifying system should be negligible. After testing many combinations of materials, the instruments at present in use have been fitted with silver slip rings and soft carbon brushes. The contact potential of this combination is higher than many others, but the variation with rubbing speed is low. The lubricating action of the carbon brushes seems to prevent the localised heating which is obtained from most metallic combinations, and results in a very low "noise" level.

Fig. 17 shows the general arrangement of a simple unit designed to fit a small diameter ($2\frac{1}{4}$") parallel shaft, held by keys and muff couplings. It is, in this case, a simple matter to remove the shaft from the mill and the unit is therefore designed to slide on the end of the shaft. In this design an inner sleeve (1) carrying the bearings and the laminated plastic insulator pads which carry the slip rings is keyed to the shaft. The slip rings (2) are made of solid silver and attached to the face of the insulator by 8 BA screws to which the leads are brazed. If necessary, the slip rings can be of copper, silver plated, but the saving in cost is small. The leads are led out of the unit to the strain gauge bridge further along the shaft. The outer cover (3) which carries an oil seal (4) is prevented from rotating by a lug welded to it and a torque link to any convenient part of the mill frame. Inserted in this outer cover is a brush box (5) machined from a solid block of a laminated plastic insulator. $\frac{1}{4}$" square soft carbon brushes (6) are mounted in suitable holders and leads from these are taken to an armoured plug such as a *Niphan* on the casing. It is advisable to have at least two brush boxes, giving two brushes in parallel on each slip ring.

The second design is rather more complicated as it is intended for shafts up to 11" in diameter with enlarged ends which prevent the unit being built up in one piece and put on the shaft from one end. It is possible to fit this unit without removing the shafts from the bearings.

The slip ring frame A (Fig. 18), made in two halves, is clamped to the shaft by endplate B. It is supported at the other end by endplate C, but this is not clamped to the shaft so that torsional strains are not transmitted to the slip ring frame. By changing

the endplate the unit can be fitted to shafts of different diameters. The slip rings D, of silver plated copper or pure silver, are mounted in laminated plastic insulators E attached to the slip ring frame with the joint displaced by 15° from the joint in the frame to reduce chatter and wear. There must be good electrical bonding between the two halves of each slip ring. This assembly is completed by ground and hard chrome plated tracks on which the brush cage bearings run.

The brush cage, F, is supported on the slip ring frame by six ball bearings, the outer races of which act as wheels running on the hard chrome tracks of the slip ring frame. It is essential that high melting point grease should be used in the bearings, and provision must be made for seals to prevent it spreading to the brush gear and slip rings. The brush holders, Fig. 19, are made from laminated plastic insulating material and screwed into the cage. In this design, three brushes in parallel were used to each ring in order to keep the contact resistance low.

The brush cages have been prevented from rotating in the larger sizes of slip ring units by having a friction lined band round the cage, with a torque link from the band to a convenient part of the bedplate.

Calibration of Torquemeter.

As the strain is of the same magnitude in each of the four gauges, the calculation of the calibration factor is a little simpler than for the loadmeter and is obtained from

$$\frac{G}{I_G} = \frac{\pi r^3 C\,(R_N + R_G}{\lambda V_N} \text{ Ton in/Amp.}$$

where G = torque to be measured.
I_G = current measured by microammeter.
r = radius of shaft.
C = modulus of rigidity of shaft.

and the other quantities are the same as in the loadmeter calibration equation.

To arrive at this, the values from the Wheatstone bridge, Fig. 20, are substituted in the general equation for V_{AB}—Equation (1), Section III, giving

$$V_{AB} = \frac{\triangle R}{R} V_N$$

But Equation (2) of Section III is

$$\frac{\triangle R}{R} = \lambda\epsilon$$

$$\therefore \quad V_{AB} = \lambda\epsilon V_N$$

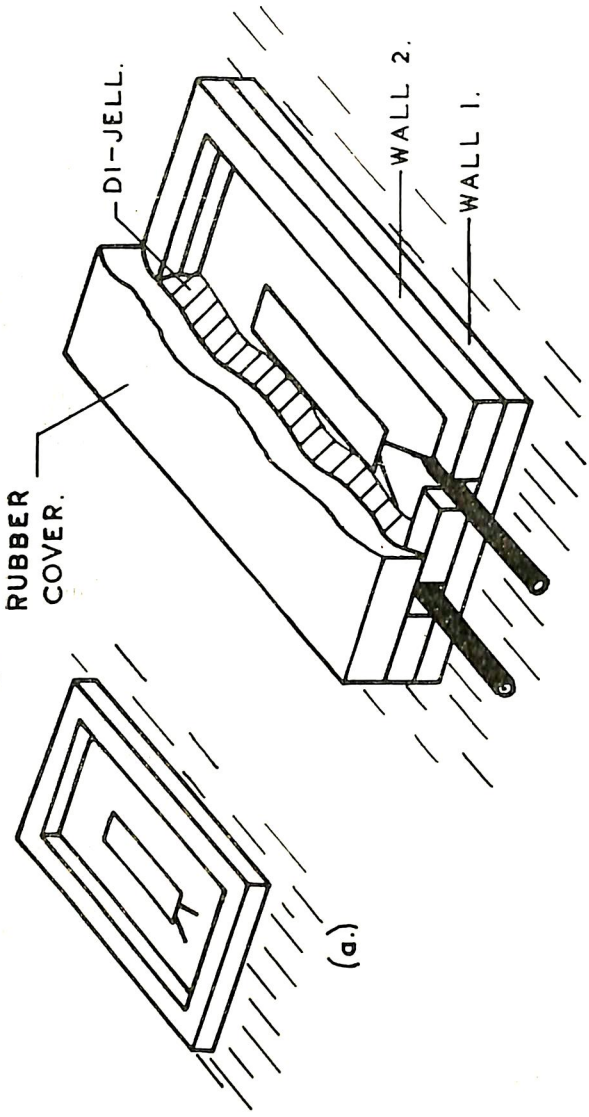


Fig. 15—Waterproofing of Strain Gauge.

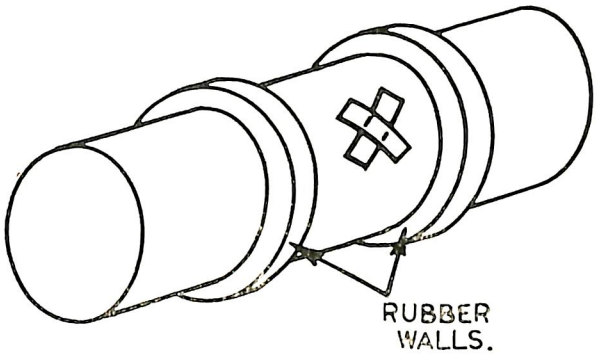


Fig. 16—Waterproofing of Strain Gauge. (Small Dia. Shaft).

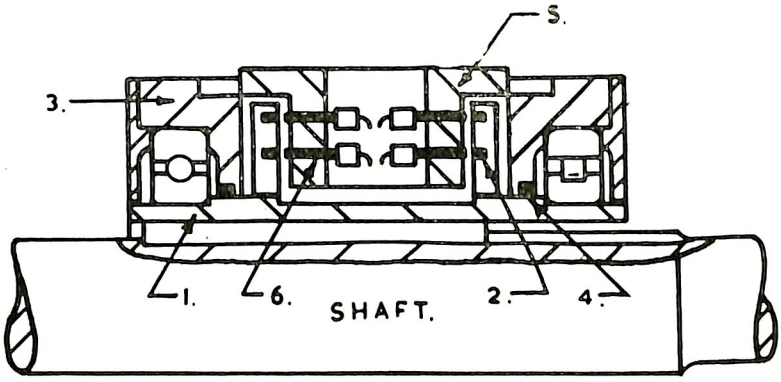


Fig. 17—Slip Rings for Small Shafts.

$$\text{and } I_G = \frac{V_N \epsilon \lambda}{R_N + R_G}$$

If J = polar moment of inertia $= \frac{\pi r^4}{2}$

C = modulus of rigidity.

ϕ = shear strain in the shaft.

Then strain at angle θ to the axis is given by

$$\epsilon\theta = \phi \sin\theta \cos\theta$$

and in this case $\theta = 45°$

$$\therefore \epsilon = \phi/2$$

If q is shear stress $q = C\phi$

$$\text{and } \frac{q}{r} = \frac{G}{J} \quad \therefore \frac{C\phi}{r} = \frac{G}{J} \text{ and } \phi = \frac{Gr}{CJ}$$

$$\text{or } \phi = \frac{2G}{\pi r^3 C} \text{ and } \epsilon = \frac{G}{\pi r^3 C}$$

Substitute in the equation for I_G above

$$I_G = \frac{\lambda G V_N}{\pi r^3 C (R_N + R_G)}$$

and the calibration factor

$$\frac{G}{I_G} = \frac{\pi r^3 C (R_N + R_G)}{\lambda V_N} \text{ Ton in/Amp.}$$

The quantities in this equation are known and it is a simple matter to scale a microammeter in ton in. Usually, however, the modulus of rigidity can only be estimated within about ± 5%, and if torque readings are required to be more accurate than this, a direct calibration has to be carried out. This is done by locking one end of the shaft and applying known twisting moments to the other end. The method of doing this depends entirely on the layout of the installation, but it is usually possible to fabricate arms to fit over wobbler necks or shaft ends without dismantling the system. If a long lever arm is used, on a shaft carrying a moderate torque, it is sometimes possible to measure the turning moment very simply by attaching a proving ring on the torque arm and loading it by an overhead crane. The angle between the chain and torque arm must be measured and allowance made if it is other than 90°. A more accurate method, suitable for high torques, is to mount a screw jack under the end of the torque arm and load the shaft by operating the jack, measuring the load by a miniature strain gauge loadmeter mounted beneath the jack. The loadmeter

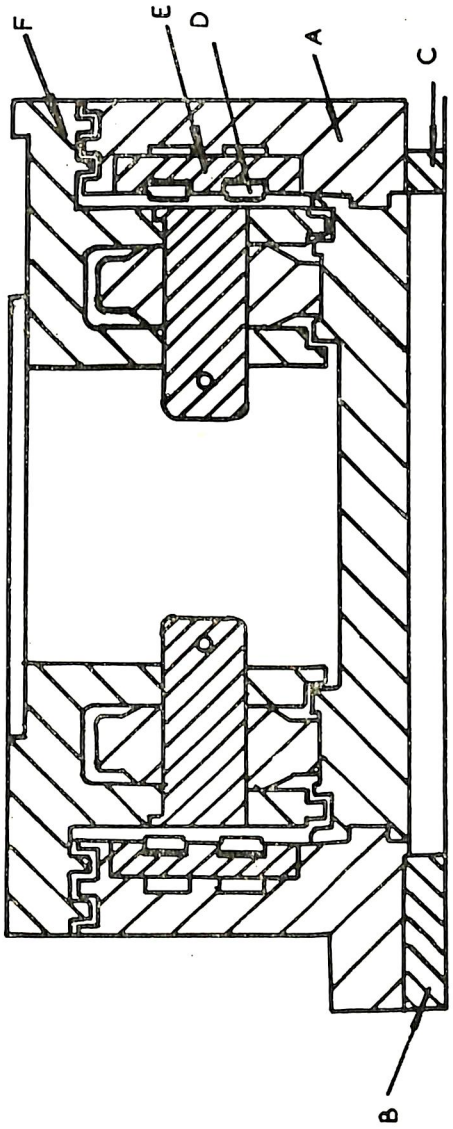


Fig. 18—Assembly of Slip Rings for Large Shaft.

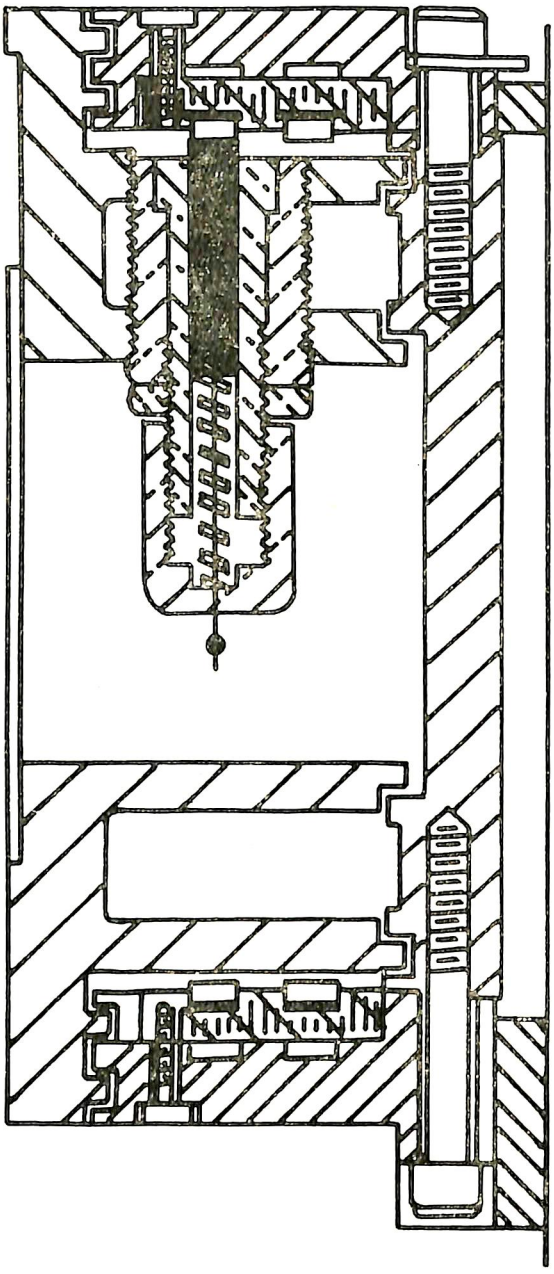


Fig. 19—Arrangement of Brush Holder

can be made by attaching strain gauges to a stainless steel tube, which is bolted to the base of the jack and the whole assembly mounted on a ball joint.

Torque Indicator Circuit.

The simple D.C. system can be used, exactly as described for the loadmeter. Normally, however, the torque shafts on a production mill are massively built and the shear strains are low, in which case the output from the Wheatstone bridge will be small, and an amplifying system should be used. Either the simple A.C. circuit or the A.C. potentiometric system described under Section III will be satisfactory.

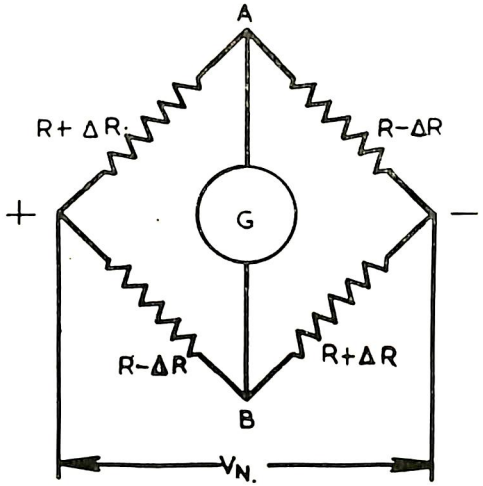


Fig. 20—Torquemeter Bridge—Gauges Strained.

V. STRIP TENSION METERS.

The type of strip tension meter to be used depends on the layout of the mill and its auxiliaries. In many reversing mills the coilers are placed so close to the mill stand that it is impracticable to use any type of instrument requiring a number of rolls in contact with the strip. In this case, the torque in the coiler shaft is measured, and tension in the strip obtained at any instant by dividing this torque by the coil radius. Suitable torquemeters for this purpose have been discussed under Section IV and all that remains is to measure the coil radius and convert it to an electrical signal in the torquemeter circuit. The mechanical design of a

follower to measure coil radius must be considered in relation to the coiler and its surroundings, and may consist of a pneumatic or hydraulic ram, or a lever and weight system, either in a pit below the coiler drum or erected above it. If possible, a ram moving radially to the coil should be used, as the movement is then equal to the change in coil radius. The follower at present in use on the B.I.S.R.A. experimental mill is shown in Fig. 21.

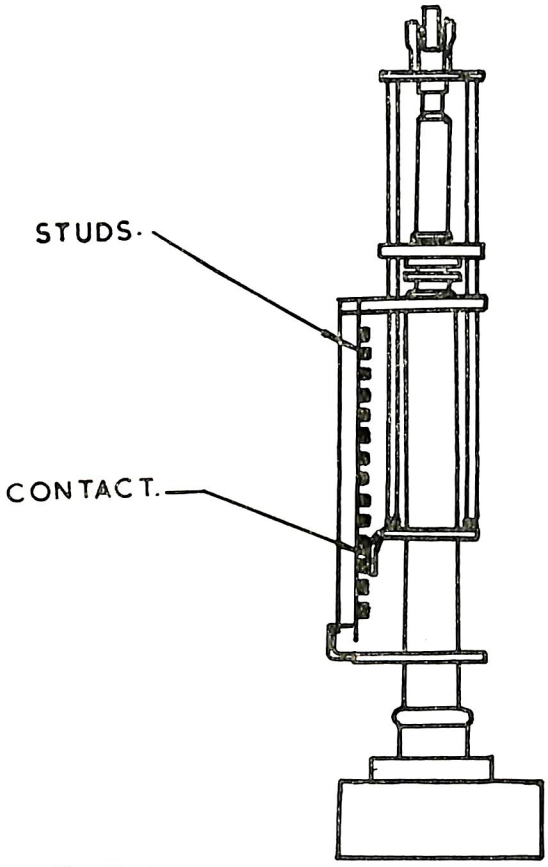


Fig. 21—Arrangement of Coil Radius Follower.

A hydraulic cylinder is mounted in a pit beneath the coiler and fed with low pressure oil to maintain the ram surmounted by an idler roll, in contact with the coil. As the build up compensation on this mill is unusual in that it covers a 4/1 range, a ram with a long stroke and hence a rather deep pit is required. An aircraft

undercarriage leg has fulfilled the requirements cheaply and effectively, the only modifications required being the clamp-on fittings for the radius measuring gear. The cylinder is mounted on the concrete base and supported from the top flange to the pit sides in such a fashion that its axis passes through the coiler drum centre. As the coil builds up, the ram is forced down against the oil pressure, but in practice there is also some measure of buffeting on the idler roll, causing heavy vibrations to be transmitted to the cylinder, which should have a small degree of flexibility incorporated in the mounting. The radius measuring gear consists of a cross-head on top of the ram, which carries two vertical rods, passing through a guide on top of the cylinder and attached to a sliding fitting on the outside of the cylinder. The slider carries spring contacts which pass over closely spaced studs mounted on an insulating strip, the distance which it travels being equal to the charge in coil radius. Each of the studs has a terminal and is wired to a bank of very accurate resistors mounted in a box on the pit side, giving the effect of a potentiometer with a resistance proportional to the change in coil radius.

The electrical system required to give a direct tension reading depends on the relationship

$$\text{Strip Tension (T)} = \frac{\text{Torque (G)}}{\text{Coil radius } (r)}$$

In order to keep the tension constant during a pass, with r increasing the coiler motor must supply an increasing torque. The voltage output from the torque bridge on the coiler shaft is, therefore, increasing with build up and the electrical signal proportional to r must be arranged to reduce the torque bridge output by the same amount, to give a final constant voltage output from the system which is proportional to tension. The simplest way is to arrange that the potentiometer increases in resistance with increase in r, and introduce it in the supply to the torque bridge, so that the voltage input and hence the voltage output from the bridge is reduced as r increases. This is shown in Fig. 22, which is identical to the torque bridge (Fig. 20), with the addition of the compensating potentiometer.

The value of the resistances required in the radius compensation is obtained very easily for a given torque bridge and coil build up. Assume for a given tension, with r_o=coiler drum radius, the output from the torque bridge is v volts. The compensation device is set to give zero resistance in this position. Taking the maximum build up ratio as $n/1$, when this build up is reached, r_o increases to nr_o and torque must, therefore, increase to nG for constant tension, giving a bridge output of nv volts. The compensation device must, therefore, introduce a resistance in the input which will

reduce the input voltage in the ratio $1/n$ so reducing the output in the same ratio and giving a final output of $\frac{nv}{n} = v$ volts.

Assuming the resistance of the system is R_N+R_G as found earlier, the compensating resistance must increase this to n (R_N+R_G), *i.e.*, the maximum resistance of the potentiometer must be equal to $(n-1)$ (R_N+R_G). The compensating resistance, therefore, varies from 0 to $(n-1)$ (R_N+R_G) in a linear fashion over the distance $(n-1)$ r_2.

If the A.C. potentiometric indicating system is used, the circuit is identical to that given for the loadmeter, with the addition of the radius compensation resistance used as a potential divider and shown in heavy print on Fig. 23.

The calibration of this type of tension meter can be done very easily, by taking a few turns of a wide strip round the coiler drum and attaching the free end to a proving ring. The ring is then anchored to a convenient point on the mill housing. The tension in the strip is obtained directly from the proving ring and the indicating meter scaled directly in tons. In order to check the accuracy of the radius compensation, this should be repeated with several different coil sizes.

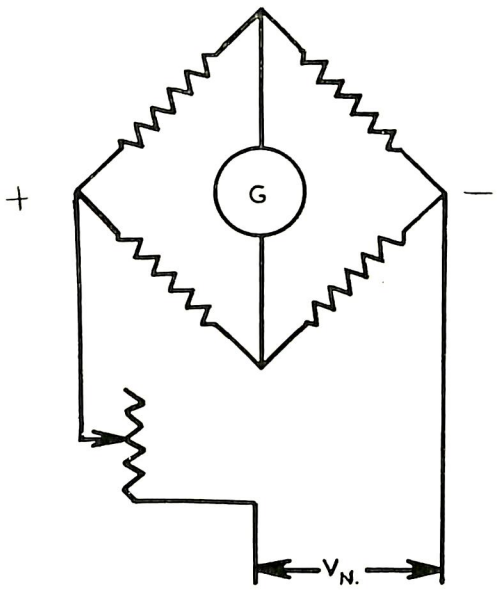


Fig. 22—Tensionmeter Circuit.

The main problem with this type of tensiometer is to protect the vulnerable spring slider and contact studs from oil and coolant carried over by the strip.

Contact Roller Type Tensiometers.

Most contact types of tensiometer depend on a roller mounted parallel to the mill work rolls which is used to deflect the strip

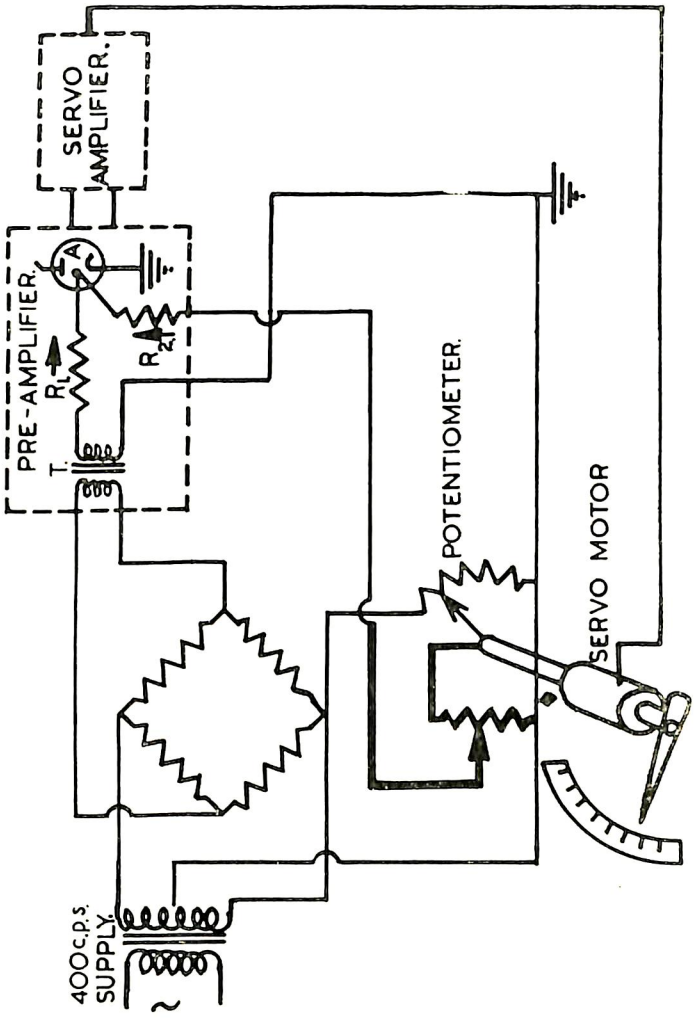


Fig. 23—Principle of A.C. Potentiometric Circuit for Tensionmeter.

from the normal pass line. If the deflection of the strip is maintained constant, the load required on the roller will give a direct indication of strip tension. Alternatively, if the roller is supported by a constant load, the magnitude of the strip deflection from the pass line will be proportional to tension. Although this second system can be very simple to apply it is not suitable for a wide range of tensions and the constant deflection method has been used in the B.I.S.R.A. prototype instruments. As it is important that the deflection should remain absolutely constant, the single roller is not very satisfactory as the pass line will change as the work rolls wear and new ones are fitted. This is overcome by mounting two idler rollers a short distance apart, with the deflecting roller between them. The angle the strip makes with the plane between the two idlers will then be constant provided that the unit is spring loaded to keep the outer rollers in contact with the strip as the pass line changes. Two possible arrangements of the three rollers are shown in Fig. 24.

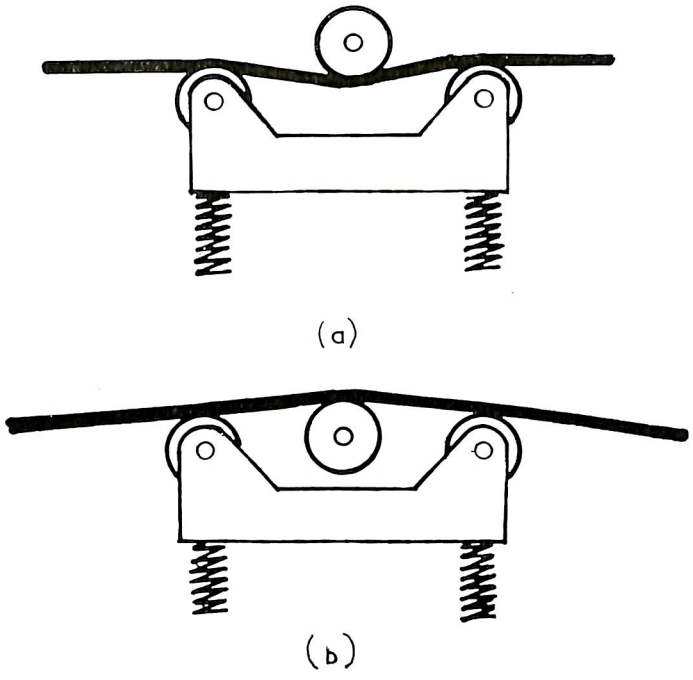


Fig. 24—Two Arrangements of Rolls for Tensionmeter.

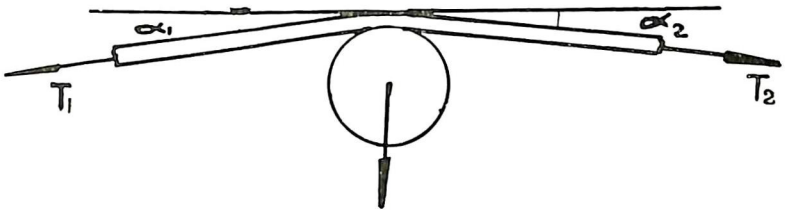


Fig. 25—Strip Deflected by Roll.

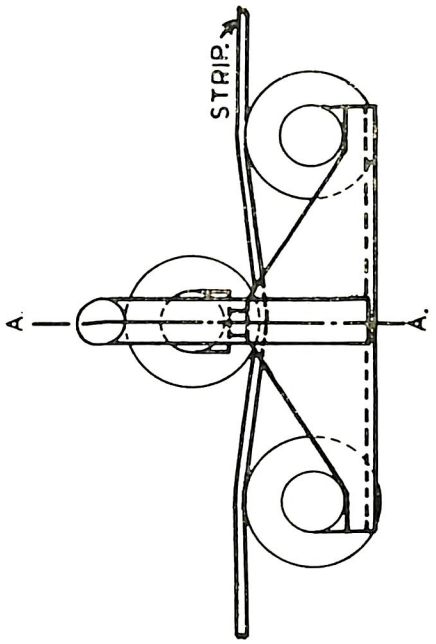
If a strip is bent over a roll, as in Fig. 25, the load required to maintain the roll in this position will be $P = T_1 \sin \alpha_1 + T_2 \sin \alpha_2$. By using three rolls α_1 is made equal to α_2 and constant so that $P = \text{Const.}\ (T_1 + T_2)$. In bending the strip over the roll, there will be some measure of plastic deformation in the strip, unless the roll diameter is very large compared with strip thickness, and if neglected by assuming $T_1 = T_2$, will give rise to errors in tension measurement in the order of 1%. Errors of this magnitude are usually of little importance and if $T_1 = T_2$,

$$P = 2 \sin \alpha\, T$$

$$\text{and Strip Tension } T = \frac{P}{2 \sin \alpha}$$

As α is constant and is obtained from the geometry of the three rollers, strip tension will be directly proportional to the load on the deflecting roller.

In designing a tensiometer the first consideration is the layout of the three rollers. That shown in Fig. 24 (*b*) is normally used in cases where it would be inconvenient to have to thread the strip in and out as is required by the arrangement shown in Fig. 24 (*a*). The rollers should be as large a diameter as possible, but obviously this is dependent on the room available on a specific mill. The deflection roller must be mounted accurately mid-way between the outer ones, and all should be axially parallel to close tolerances. There are many ways of measuring the load on the deflecting roller, but whatever system is used, the vertical movement must be kept to a minimum in order to maintain α constant. In the prototype models the maximum movement is in the order of ·001″. Fig. 26 shows a small tensiometer suitable for strip up to 6″ wide. The deflecting roller is supported on two stainless steel tubes which are fitted with strain gauges to form loadmeters, as described under Section III. This instrument can be calibrated by deadweight loading on the deflector roll, dividing this by the measured angle α to obtain tension in tons, or by direct pull on a proving ring with strip threaded up as described earlier.



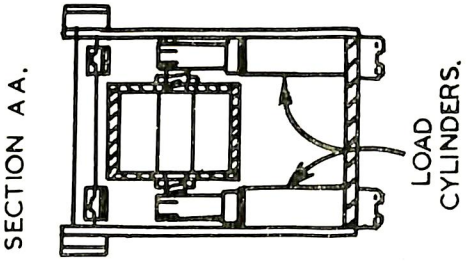


Fig. 26—Three Roll Tension Meter.

Fig. 27 shows a larger tensiometer designed for a wide strip tandem mill. In this case the deflecting roll bearings are mounted in pivoted side plates which are supported in the correct position by loadmeters made up from stainless steel tube. An alternative arrangement would be to use side plates acting as bell crank levers, linked together to pull on a tension link, fitted with strain gauges.

In either of these instruments the electrical indicating circuits will be exactly as described under Section III for loadmeters, and the indicator can be scaled directly in tons tension.

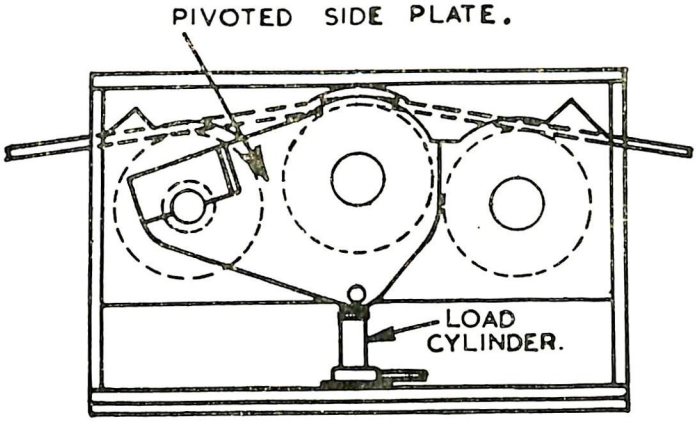


Fig. 27—Three Roll Tension Meter. (Side Cover Removed).

VI. THE GAUGEMETER.

Theory of Gaugemeter.

If rolls and mill housings were perfectly rigid the measurement of gauge would present no problem as the outgoing strip thickness would always be the same as the initial gap between the rolls. In practice, of course, this condition can never be realised and when material enters the rolls the mill "springs" so that the final gauge is greater than the initial roll gap. Stated very simply, the B.I.S.R.A. gaugemeter measures the initial roll gap and the mill spring, adding them together to indicate the outgoing strip thickness on a single meter. The measurement of roll gap is direct, but the measurement of mill spring is obtained indirectly from roll load by applying Hooke's Law to the rolls and mill housing.

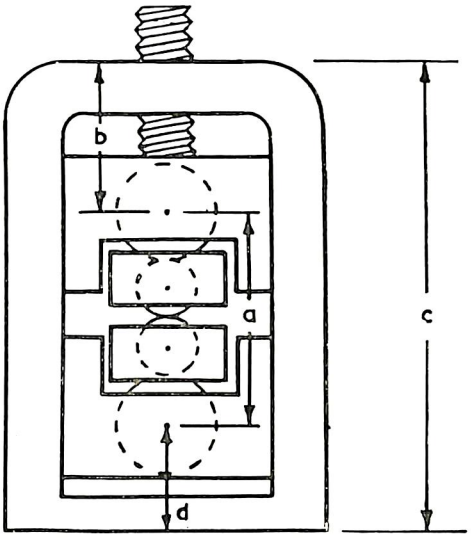


Fig. 28.—Mill "Spring."

Fig. 28 shows diagrammatically a four high mill with the work rolls set to a known gap. If strip is entered between the rolls, the mill will "spring" due to roll flattening, elastic compression of the screw and part of the back up chocks, stretch of the housing and bending of the bridge, *i.e.*, total spring is the sum of the changes in length of *a*, *b*, *c* and *d*. Each of these components can be treated as a simple elastic system obeying Hooke's Law, so that the change in length of each is directly proportional to the applied load. It would be expected, therefore, that the total mill spring would be directly proportional to the applied load. This can easily be checked experimentally on a mill equipped with loadmeters. The rolls are set to a known gap, and a series of strips of varying thickness rolled, recording the roll load and final thickness of each. By substracting the initial roll gap from the final strip thickness the mill spring is obtained, and this is plotted against load to give a curve of the form shown in Fig. 29. As expected, the relationship is linear over most of the range, but there is a pronounced curve as the load approaches zero, and a slight drift from the straight line under maximum load conditions. The curvature lies well outside the normal mill operating range and, therefore, is not considered to be important.

When rolling very thin material it is common practice to force the rolls together under a preload before entering the strip and in

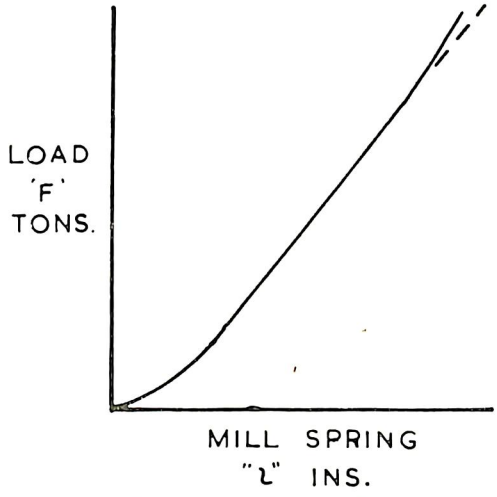


Fig. 29—Load/Spring Curve.

this case the initial roll "gap" will be a negative quantity. If the rolls are set so that they are just in contact, then forced together by screwing down, the distance through which the screws move will be equal to the total "spring" and by reading the load at various screw positions another curve identical to that of Fig. 29 can be plotted. A very large number of tests on several mills have shown that there is a unique curve for each mill, and if the slope of the straight portion is measured the constant obtained is the modulus M of that particular mill. For a measured load it is then only necessary to apply the simple relationship $\frac{F}{M} = \ell$ to obtain the mill spring ℓ directly in inches.

If the initial roll gap is S_o inches and the load measured at a given instant is F tons, the outgoing strip thickness h will be the sum of the initial gap and mill spring,

$$i.e., \quad h = S_o + \frac{F}{M}$$

This equation will still apply if S_o is negative, *i.e.*, if the rolls are preloaded.

Practical Application.

There are many practical ways of obtaining a continuous solution of this equation, but all the existing instruments make

use of an electrical method. There is already an electrical signal from the loadmeters which is proportional to F, and M is a measured constant. This leaves the quantity S_o which can be transformed to an electrical signal in many ways. In a normal screw loaded mill the screw can be used as a micrometer by counting the number of turns. One way of doing this is to mount a drum made from insulating material on top of the screw and wind resistance wire round it, the pitch of the wire being the same as that of the screw threads. A fixed brush in contact with the wire will then short out part of the resistance, and give an electrical signal proportional to the movement of the screw. This has the advantage of being directly attached to the screw and so eliminating backlash effects but is rather a delicate piece of equipment to be mounted in an exposed position on the mill head gear. A neater method is to mount a *Magslip* transmitter on the head gear and drive it from a gear mounted on the screw. Most screws are driven by a gear and sliding key and it is usually possible to bolt a small gear to drive the magslip directly onto the face of the screw driving gear. The single pair of small gears can be accurately made to give a very small backlash effect. The signal from the magslip transmitter is picked up by a magslip receiver at any convenient position remote from the mill, this receiver being coupled to a potentiometer from which a resistance proportional to screw position is obtained. Many mills are fitted with *Selsyn* indicators to show screw position, but in general they are driven through a train of spur gears and there is a considerable backlash when the screws are reversed.

D. C. Circuit.

Having fitted loadmeters and screw position indicators to a mill, all that remains is to connect them up in a suitable circuit. A very simple circuit could be used to add the electrical quantities proportional to S_o and F/M but it is usually more convenient to set the required gauge at the control desk and indicate deviations from this gauge on a meter. This introduces another factor into the equation. If h^1 is the required gauge, and as before h is the gauge actually rolled, the error being $\triangle h$

$$\text{then} \quad h = h^1 + \triangle h$$

$$\text{and} \quad h^1 + \triangle h = S_o + \frac{F}{M}$$

$$\text{or} \quad \triangle h = S_o + \frac{F}{M} - h^1$$

A D.C. circuit capable of giving a continuous solution of this equation is illustrated diagrammatically in Fig. 30. The circuit (A) is identical to that given in Section III for two loadmeters

indicating total load. If F/M is represented by the voltage output from this circuit, the calibration factor volts per inch of mill spring is obtained. Circuit (B) represents S_o. Resistance (*a*) is proportional to the screw position and has an adjustable zero (*b*) which is set so that negative roll settings can be obtained. The calibration factor volts per inch of screw movement must then be matched to that of circuit (A) by adjusting resistance (*c*). Circuit (C) represents h^1. Resistance (*d*) is a decade box, with the steps in resistance calibrated directly in fractions of an inch so that the required gauge can be set on the dials. Again the calibration factor volts per inch of required gauge must be matched to the other two circuits by adjusting resistance (*e*). The adjustments (*c*) and (*e*) will obviously depend on the mill modulus. Another possible circuit would have a single adjustment for mill modulus in the loadmeter circuit, but this is complicated by the fact that, although not shown, there are two loadmeter bridges, and a small balancing adjustment would still be required between circuits (B) and (C).

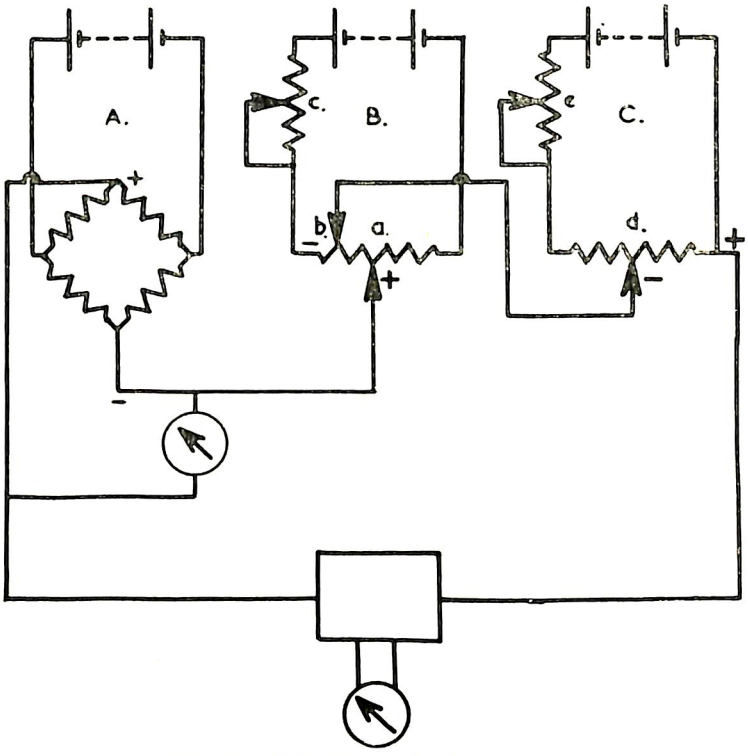


Fig. 30—D.C. Circuit for Gaugemeter.

The output from the three circuits is combined to give the solution of the equation and amplified to give a direct reading of gauge error on a suitably calibrated ammeter.

By using the sum of both loadmeter outputs in the circuit, a reading of average gauge across the width of the strip is obtained. It is possible to take the screw position signal from one screw only, but if the strip is wedged the screws may not be in identical positions, and a better average will be obtained by incorporating a signal representing the mean of the two screw positions.

A.C. Circuit.

A rugged industrial type installation with A.C. circuits and automatic push button zero set is now undergoing trials, but details of the circuits involved are beyond the scope of this pamphlet. A full account of this installation will eventually be published in the technical press by Carlisle and Alderton.

Performance of the Gaugemeter.

The instrument is capable of a high degree of accuracy, especially when used as a comparator measuring within a small range. If measurements over a very wide range of mill loads are required, slight curvature of the "straight line" modulus curve will have an appreciable effect and a non-linear resistance may have to be introduced into the circuit to allow for this. There is some evidence that this slight curvature does exist in some mills. More important than this, is the effect of change in roll diameter on the absolute measurement. Any change due to wear or change in temperature is reproduced by the same amount as an error in the zero setting and hence S_o. This effect can be kept within reasonable limits by frequent use of the automatic zero set. Another source of error which may arise is that due to slight changes in mill modulus caused by rolling widely different widths of strip. When rolling narrow strip all the load is concentrated on a short section of the roll barrel, giving greater roll flattening than when it is distributed along all the length. In this case the mill modulus should be determined for the minimum and maximum widths to be rolled and if there is an appreciable difference, the circuits will have to be matched at each major change in strip width. This needs to be the work of a few seconds only.

In spite of the present limitations mentioned, this type of gaugemeter has tremendous advantages over any other existing instrument. As the measurement is made through the work rolls, there are no delicate instruments near the pass line to be damaged by the tail end of the strip or a cobble, and the gauge is measured at the earliest possible point; actually in the roll gap. The

accuracy will be independent of change in hardness of the strip' presence of rolling oil or coolant, or change in strip tension. The indicating circuit can be designed to give an extremely rapid response and it is actually possible, even on a high speed mill, to indicate the change in gauge at each revolution of the work rolls, due to the roll eccentricity.

The unique feature is that this gaugemeter can be used as the basis of an extremely high speed automatic gauge control.

VII. AUTOMATIC GAUGE CONTROL.

Although not strictly coming within the classification of "Instruments," the gauge control systems described depend on the loadmeter and, in some cases, the gaugemeter or tensiometer for their operation.

Control of Gauge by Strip Tension.

If the equation for strip thickness given in Section VI, $h = S_o + F/M$, is considered, it will be seen that one criterion for constant gauge is that S_o and F/M must each remain constant. By working to a fixed screw setting, S_o is maintained constant and M is constant by definition. The problem then reduces to keeping the load F constant without adjusting the screws. The load required to deform the strip depends on many factors, including hardness of strip, surface finish of rolls and strip, lubrication, roll radius and applied strip tension. Of these, only the tension is directly under the control of the operator, and the load can therefore be held at a constant value by adjustment of back tension, front tension, or both. Increasing either of the tensions will decrease the roll load.

A simple but accurate method of gauge control is based on this principle. The operator sets the screws to give the required gauge under a medium tension, then maintains the gauge simply by adjusting tension to keep the load constant. This system is capable of a great deal of refinement, but the only real advantage over normal gauge control by screwdown is that it is possible to hold the gauge to rather closer tolerances. There is still the lag between the operator noting a change in load and applying the correction. In order to overcome this, a completely automatic system capable of operating at high speeds has been built and tested.

In the automatic system, the load for a given h and S_o is calculated from the above equation and set on an indicator. The circuit from this is so arranged that for a given setting the output is identical to that from the loadmeter at the equivalent load. The two signals are balanced, and the resultant fed into an amplifier.

When running at the correct load, there will be no output from the amplifier, but any variation in load will cause either a positive or negative out of balance voltage which is amplified and used to control the coiler motor through a rotary amplifier such as a *Metadyne* or *Amplidyne*. In order to prevent the strip throwing slack, or breaking, a tensionmeter must be fitted and the output circuit arranged so that when the tension limits are reached further control will be prevented. It can also be used to cut out the control if the strip breaks.

This system is capable of controlling gauge to within ±0·0002″ but is limited to cold rolling and to mills equipped with powerful coiler motors. A more versatile method of control is to vary the load either hydraulically or by screwdown.

Control of Gauge by Load Variation.

A simple system of A.G.C. based on the gaugemeter and suitable for immediate application to many production mills is installed on the B.I.S.R.A. 4-high experimental mill. The installation consists of a gaugemeter with an A.C. potentiometric indication of gauge error, switches and relays to operate the screwdown motors and a braking system to stop the screwdown motors very quickly when the contactor is released. The gauge error indicator is mounted in a prominent position on the mill frame and micro switches are fitted behind the dial in such a position that they are operated by cams mounted on the pointer driving spindle whenever the pointer moves outside the present tolerances. Assuming a tolerance of ±·0006″ is required on the finished gauge, the micro switches are set to operate at say ± ·0004″ to allow a margin of safety. If the strip begins to run thicker than the required gauge, this is shown on the gauge error indicator, and when the pointer reaches ·0004″ the appropriate micro switch is energised, starting the screwdown motors through relays and contactors. Load is applied until the strip begins to return to gauge, and as the pointer returns through ·0004″ the micro switch is released, and the screwdown motors stopped. Normally screwdown motors take several seconds to run down to rest, and in this time the gauge may overshoot to −0·0004″, in which case the motors would be started in the other direction and a stable position could not be reached. The simplest way to overcome this is to fit the screwdown motors with powerful brakes which come into operation as soon as the contactors are released. The type of braking most suitable for individual motors must be selected. With A.C. Series wound motors, it is possible to inject D.C. into the field windings as soon as the A.C. is switched off, giving a very powerful braking action.

The great advantage of this system is that it can be adapted to fit most existing mills quickly and cheaply. Very little modi-

fication to the mill wiring is required and in the event of the control breaking down it is possible to continue rolling under normal control. The motors can be made to start very quickly when the off gauge tolerance is reached, but the time to correct is then dependent on the screwdown speed. For sudden changes in section, as at a weld, or on very thin hard strip, the time to correct may run into several seconds, and for very accurate and rapid control the screws should be controlled continuously and not just when the tolerance is exceeded.

In order to do this, a continuous solution of the equation $\triangle h = S_o + F/M - h^1$ is required. It has been shown that this solution can be obtained from a simple D.C. gaugemeter circuit, the output being an electrical signal proportional to $\triangle h$. This output is amplified and fed to the control winding of a rotary amplifier which is used directly to control D.C. screwdown motors. In fitting this to a new mill, powerful D.C. screwdown motors would be specified, so that a rapid correction could be applied.

A similar system could be used on a hydraulic mill. In an installation already tested, normal load cylinders are mounted between the ram and chock, and the value of S_o is obtained by mounting a light metal beam in such a position that movement of the ram bends it. Strain gauges on the beam measure the deflection which is related to S_o and the gaugemeter circuit completed as before. The error signal from the gaugemeter is amplified, and fed into a hydraulic amplifier operating a valve which varies the pressure in the hydraulic cylinder continuously to maintain constant gauge.

Further details of all the above methods of A.G.C. can be obtained from technical articles already published and listed in the bibliography.

VIII. LOAD MEASUREMENT IN SECTION MILLS.

In the rolling of sections the loadmeters do not always indicate the total resultant load on the rolls as there may be substantial end thrusts. A small experimental mill suitable for rolling sections in lead has been built, incorporating instruments to measure vertical load, end thrust and side thrust. It is a simple two high mill, with the top chocks sliding in the housings and directly loaded by screws in the normal way. The bottom chocks, however, instead of being fixed in position are suspended from four links, and prevented from moving forwards and sideways by other links. The arrangement of the links is shown in Fig. 31. Attached to the links are strain gauges, and it is possible to measure directly

the forces on the roll. The readings will be affected by the drive shaft to a certain extent, but the errors can be reduced to a minimum by keeping the shaft and roll axes in line and incorporating a coupling which will allow free end float.

An installation of this nature would not be satisfactory under production conditions but if the links and strain gauges were suitably protected it could be incorporated in a production type mill for experimental work on hot steel.

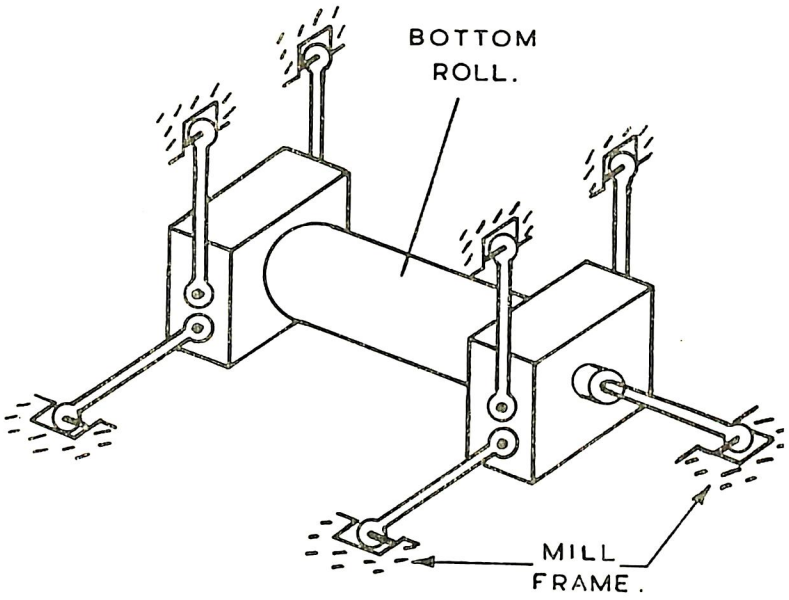


Fig. 31—Arrangement of Measuring Links

Calibration of Links.

Four strain gauges are attached to each link in order to provide temperature compensation. They are arranged horizontally and vertically at each side of the link and wired into a Wheatstone bridge network as shown in Fig. 32. The discussion of the load-meter calibration (Section III) will apply to this network and as before

$$I_G = \frac{(1+\sigma)\ \lambda \epsilon V_N}{2\ (R_N+R_G)}$$

If the load applied to each link is P tons and the cross-sectional area of the link is A sq. ins.

$$\epsilon = \frac{P}{AE}$$

and substituting for ϵ,

$$I_G = \frac{(1+\sigma)\,\lambda V_N P}{2AE\,(R_N+R_G)}$$

i.e., Calibration Factor

$$\frac{P}{I_G} = \frac{2\,AE\,(R_N+R_G)}{(1+\sigma)\,\lambda V_N} \text{ Tons/Amp.}$$

Everything in this equation is known and an ammeter can be scaled directly in tons. For accurate measurements, the link should be calibrated directly by subjecting it to known loads in a tensile testing machine and scaling the ammeter in accordance with the indicated loads.

A design strain in the links of about 0·1% at maximum load will give a measurable output without reducing the stiffness of the mill unduly.

The tension links mentioned in connection with the three roll tensionmeter are calibrated in exactly the same way.

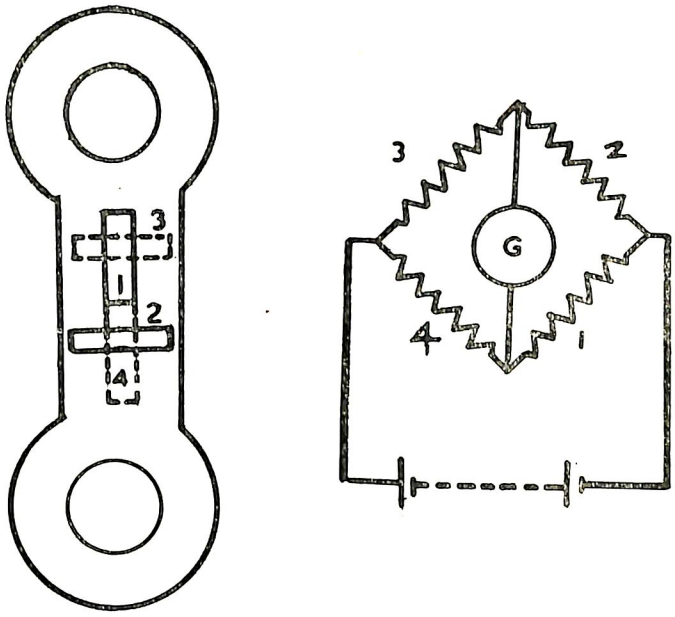


Fig. 32—Arrangement of Strain Gauges on Links.

IX. THE B.I.S.R.A. 14″ EXPERIMENTAL MILL.

Many of the instruments described are in continuous use on the recently installed 14″ experimental mill. It is a Robertson 4-high mill accommodating work rolls from 3⅛″ to 7″ diameter and with 14½″ diameter back up rolls. Screwdown is by two 5 H.P. series wound A.C. motors giving a maximum screwdown load of 300 tons. The speed of the 750 H.P. main motor can be controlled accurately from 0 to 955 r.p.m., giving a maximum strip speed of 1750 f.p.m. with the 7″ rolls. Maximum torque available is 65 ton in. for short periods. Under normal running conditions the maximum strip tension available is 2 tons per side at the full coil build up of 4/1, but this can be doubled for short periods.

A general view of this mill is shown in Fig. 33.

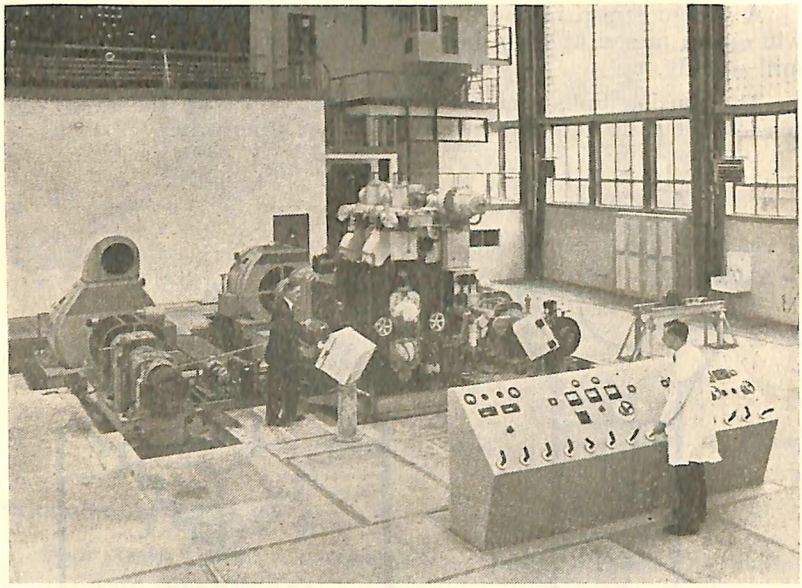


Fig. 33—General View of Experimental Mill.

Fig. 34 shows a loadmeter in position. It will be seen that the length/diameter ratio is much greater than would be normally used in a production installation. There are two reasons for this. First, as it is used to measure loads for research work a very high degree of accuracy is required, and secondly, it was designed to accommodate three complete strain gauges bridges to enable comparisons to be made between the various measuring and in-

dicating systems. At the moment each loadmeter is fitted with two bridges of low resistance "foil" gauges and one bridge of high resistance wire gauges. One foil gauge bridge is in permanent use in an A.C. potentiometric system, indicating loads on the large scale dials shown in Fig. 34, but it is possible to couple up the wire gauge bridge in a simple D.C. circuit in a very short time.

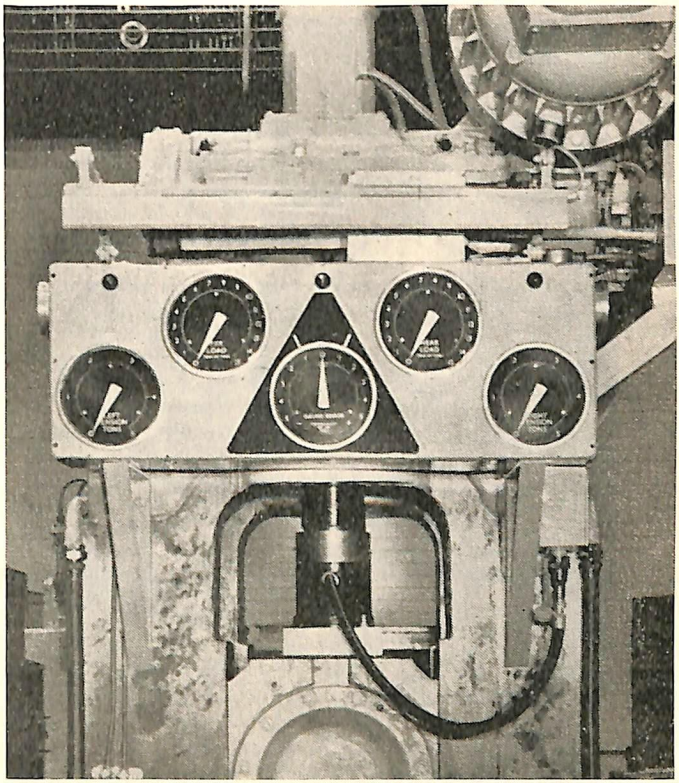


Fig. 34—Loadmeter and Indicator Panel.

The torque transmitted to the rolls is measured by high resistance gauges in a simple D.C. circuit. Figs. 35 and 36 show the torquemeters in position in the mill, and in the calibration rig.

The torque in the coiler shafts is measured by high resistance gauges, cemented to the shafts by durofix, and coupled in a potentiometric A.C. circuit. After correcting for coil radius the tensions are displayed on the instrument panel—Fig. 34.

The instrument panel can be photographed by a cine-camera mounted on the control desk to give a continuous record of the changes in load, tension and gauge during a pass. Alternatively, the loads, torques, tensions, gauge, mill speed and any other quantities required can be displayed on a small instrument panel behind the mill to be photographed. Provision is also made for high speed recorders to be coupled to any of the circuits.

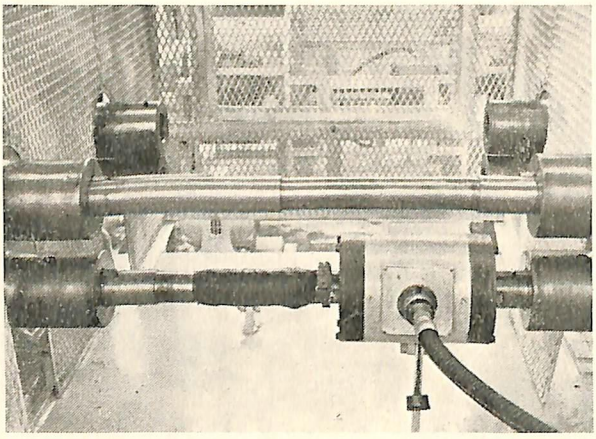


Fig. 35—Torquemeter in Mill.

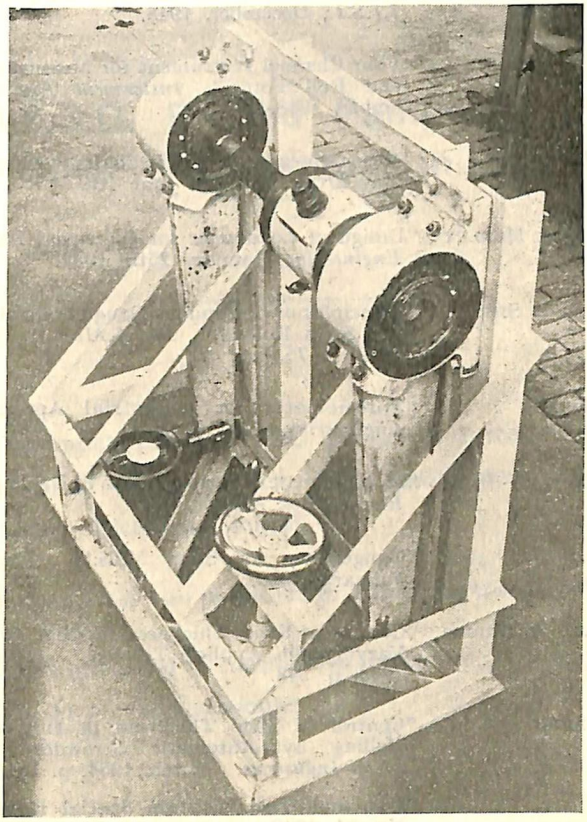


Fig. 36—Torquemeter in Calibration Rig.

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28. $\frac{7}{8}$" ,, ,, ,, (40 ton yield).
29. 1" ,, ,, ,, (40 ton yield).
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